

2016

Eliminating Magnetic Forces from the Surface Tension Measurement of Magnetic Surfactants

Emily Koehler

University of Mississippi. Sally McDonnell Barksdale Honors College

Follow this and additional works at: https://egrove.olemiss.edu/hon_thesis



Part of the [Chemical Engineering Commons](#)

Recommended Citation

Koehler, Emily, "Eliminating Magnetic Forces from the Surface Tension Measurement of Magnetic Surfactants" (2016). *Honors Theses*. 307.

https://egrove.olemiss.edu/hon_thesis/307

This Undergraduate Thesis is brought to you for free and open access by the Honors College (Sally McDonnell Barksdale Honors College) at eGrove. It has been accepted for inclusion in Honors Theses by an authorized administrator of eGrove. For more information, please contact egrove@olemiss.edu.

ELIMINATING MAGNETIC FORCES FROM THE SURFACE TENSION
MEASUREMENT OF MAGETIC SURFACTANTS

by
Emily Anne Koehler

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of
the requirements of the Sally McDonnell Barksdale Honors College.

Oxford
May 2016

Approved by

Advisor: Dr. Paul Scovazzo

Reader: Dr. John O'Haver

Reader: Dr. Adam Smith

© 2016
Emily Anne Koehler
ALL RIGHTS RESERVED

ACKNOWLEDGMENTS

I would not have accomplished the many goals I set for myself without the help, love, and guidance of so many different people. I would first like to thank my parents, Susan and Steve Koehler, for continually supporting me in all my pursuits from theater to engineering and everything in-between. Thank you Jacob Wolfe for your constant support and encouragement these past three years; I am excited to see where our future together takes us knowing I can tackle on any challenge with you at my side. Thank you Dr. Paul Scovazzo for taking on the challenging task of being my thesis advisor. I know I made it difficult at times, but you held me accountable and motivated me to persevere for which I really am grateful. Likewise, I want to thank all the professors who also guided me and encouraged me to grow throughout my academic career especially Dr. John O'Haver, Dr. Adam Smith, Dr. Elizabeth Ervin, and David Carroll. I would like to thank the friends I made during my four years at Ole Miss who have helped me to learn more about myself that I ever could have on my own. Finally, I would like to thank the Sally McDonnell Barksdale Honors College for giving me the opportunity to participate in their program and write this thesis.

ABSTRACT

Surfactants have many applications due to their ability to reduce the surface tension between two phases. Magnetic surfactants, a relatively new form of surfactants, offer the possibility of further controlling a surfactant system by using an external magnetic field to induce alignment on the molecular level. One method of studying a magnetic field's effect on the magnetic surfactant system involves analyzing the change in surface tension at varied solution concentrations both in and outside a magnetic field. The pendent drop method uses the downward gravitational force on a droplet suspended from a needle to find the surface tension based on the drop's shape. Previous results with the magnetic surfactant $[\text{C}_{16}\text{TA}]_2\text{CoCl}_2\text{Br}_2$ show an overall decrease in the surface tension of the solution when suspended over a permanent magnet. While this change could point to the surfactant's molecular realignment, permanent magnets produce a magnetic field gradient that could directionally pull the surfactant towards the magnet, potentially acting as a downward force not accounted for in the pendent drop correlations that only use gravity. This scenario would also result in a calculated surface tension change. We continued the initial investigation by replicating it with the magnetic surfactant $\text{C}_{16}\text{TAFcCl}_3\text{Br}$ as well as analyzing its surface tension inside a parallel magnetic field to remove the gradient and eliminate the opportunity for varied effective gravity on the drop. The obtained results match the trend of a surface tension reduction when inside a magnetic field which suggests the idea of induced alignment of the surfactant; however, the data only supports this clearly when using the higher magnetic field levels.

Table of Contents

LIST OF TABLES AND FIGURES.....	vi
1. INTRODUCTION AND LITERATURE REVIEW	1
1.1 Characteristics of Surfactants and Magnetic Surfactants.....	1
1.2 Methods of Measuring Surface Tension	4
1.3 Magnetics and Their Effects.....	6
2. EXPERIMENTAL.....	9
2.1 Materials	9
2.2 Equipment.....	10
2.3 Procedures.....	11
3. RESULTS	17
3.1 Surface Tension Measured over a Permanent Magnet	17
3.2 Surface Tension Measured in the Parallel Magnetic Field.....	19
4. DISCUSSION AND CONCLUSION	21
REFERENCES	22

LIST OF TABLES AND FIGURES

Table 1. Emperical Constants Used in Equation 2 [6]	5
Table 2. Volume Required to Create 25 mL of Varied Concentrations of Magnetic Surfactant Solution with a Dysprosium Counter Anion	14
Table 3. Volume Required to Create 25 mL of Varied Concentrations of Magnetic Surfactant Solution with an Iron Counter Anion	15
Figure 1. Illustration of a Micelle Formed after a System Reaches the CMC [3]	2
Figure 2. Molecular Structure of the Cationic Surfactant, CTAB ($C_{19}H_{42}BrN$).....	2
Figure 3. Molecular Structure of a Cationic Magnetic Surfactant Using Iron as the Counter Anion.....	2
Figure 4. Concentration Reduction Seen in Solutions with the Magnetic Surfactant $[C_{16}TA]_2[CoCl_2Br_2]$ Under a Magnetic Field Strength of 0.6-0.47 T [Unpublished Data] 3	
Figure 5. Illustration of the Variables Used in Calculating Surface Tension from the Pendent Drop Method	5
Figure 6. Setup Used for Taking Surface Tension Data over the Permanent Magnet.....	10
Figure 7. Setup Used for Taking Surface Tension Data inside a Parallel Magnetic Field	11
Figure 8. Effect of a Permanent Magnet on the Surface Tension of the Magnetic Surfactant $[C_{16}TA][DyCl_3Br]$ Under a Magnetic Field Strength of 0.6-0.27 T	17
Figure 9. Effect of a Permanent Magnet on the Surface Tension of the Magnetic Surfactant $[C_{16}TA][FeCl_3Br]$ Under a Magnetic Field Strength of 0.6-0.13 T	18
Figure 10. Example Photo of the Shape Analysis Performed on the Droplets	19
Figure 11. Surface Tension Measurements of the Magnetic Surfactant $[C_{16}TA][FeCl_3Br]$ Performed in a Parallel Magnetic Field at Varied Field Strengths ...	20

1. INTRODUCTION AND LITERATURE REVIEW

1.1 Characteristics of Surfactants and Magnetic Surfactants

Surfactant application has noticeably expanded over the past few decades from oils, pharmaceuticals, and detergents to include applications in electronic printing, microelectronics and much, much more. The term surfactant comes from a contraction of the term surface-active agent due to the chemical's ability to adsorb onto the surface of a system and change the free energy at the interface. This interfacial free energy is reflected by the minimum work required to create and maintain the interface: surface tension [1]. More visibly, surface tension manifests itself as the force exerted per unit length of surface that minimizes the unfavorable interaction between two different phases by minimizing the surface area [2]. Therefore, as a surfactant adsorbs onto the surface it will also alter the surface tension between the two phases; however, only a small concentration can actually adsorb in this manner [1].

After a solution concentration reaches a certain threshold known as the critical micelle concentration (CMC), the surfactants form aggregates, known as micelles, instead of adsorbing on the surface and reducing the surface tension [2]. The micelles, shown in **Figure 1**, form because of the surfactant's amphipathic structure which includes a hydrophilic group, the head, on one end of the molecule and a hydrophobic group, the tail, on the other as seen in **Figure 2**. The ionic charge of a surfactant's head group classifies it in one of four groups: anionic, cationic, zwitterionic, or nonionic [1].

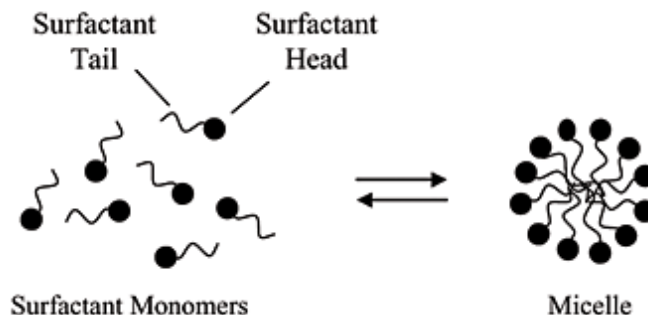


Figure 1. Illustration of a Micelle Formed after a System Reaches the CMC [3]

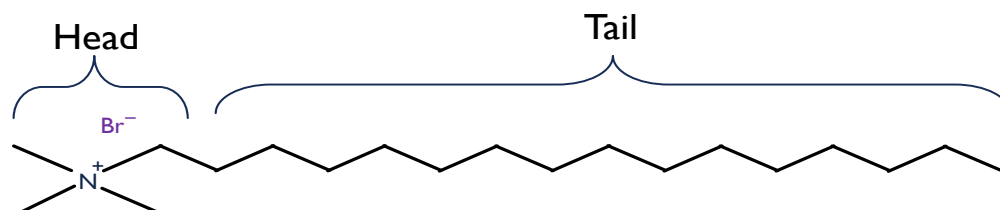


Figure 2. Molecular Structure of the Cationic Surfactant, CTAB ($C_{19}H_{42}BrN$)

A relatively new form of surfactants, magnetic ionic surfactants, takes the common cation surfactant and replaces its counter anion with metal complex anions with high effective concentrations of metal centers such as iron as seen in **Figure 3** [4]. These recently reported [5] magnetic ionic liquid surfactants provide new opportunities with molecular-level magnetic fluids different from the previous magnetic liquids comprised of magnetic particles suspended throughout a carrier fluid. Some studies have investigated the change in the magnetic surfactants effect on the surface interactions between water and air [5]. Additionally, they also tested the effect of the surfactant's magnetic response on surface tension by measuring the surface tension about 1 mm away

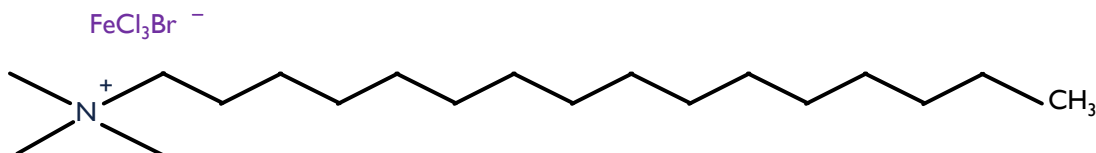


Figure 3. Molecular Structure of a Cationic Magnetic Surfactant Using Iron as the Counter Anion

from a 0.4 T permanent magnet. In addition to the surface tension reduction seen just by changing the counter anion, the imposed magnetic field surface further decreased the surface tension [5]. As seen in **Figure 4**, previous unpublished data taken in-house also showed similar results when analyzing the surface tension of a cationic magnetic surfactant with cobalt as the ferromagnetic counter anion. The magnetic surfactant's capacity to reduce the surface tension from its parent surfactant both in and outside a magnetic field supports the idea that they are bifunctional, both from its intrinsic surface-active abilities and from its magneto-responsive capabilities [4]. The reported reduction in surface tension could be due to an induced alignment of the magnetic counter ions; however, it has been suggested that the observed change could be due to other factors that this study investigates.

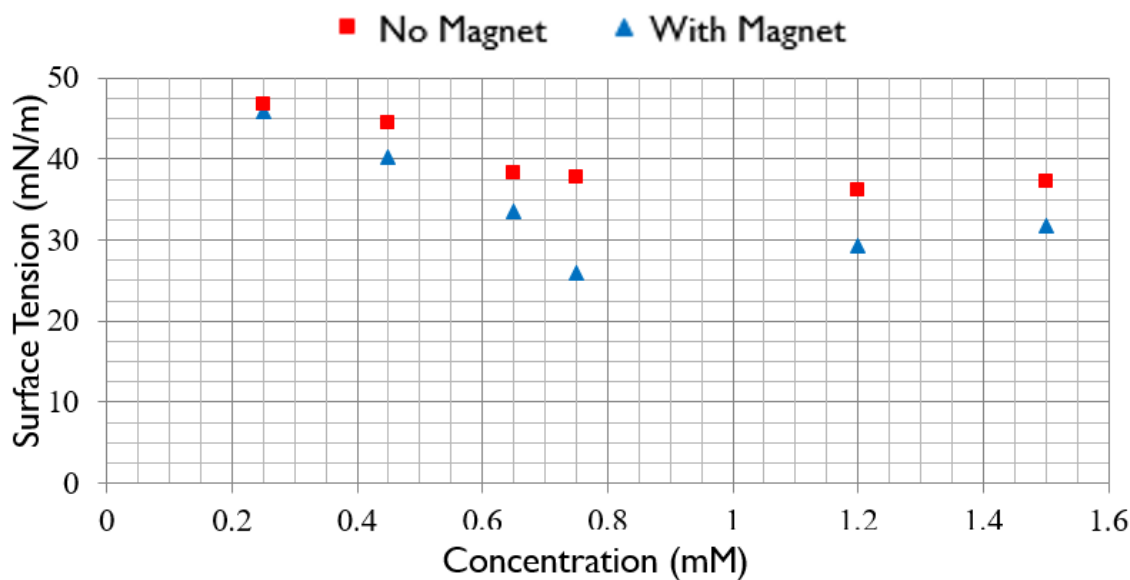


Figure 4. Concentration Reduction Seen in Solutions with the Magnetic Surfactant $[C_{16}TA]_2[CoCl_2Br_2]$ Under a Magnetic Field Strength of 0.6-0.47 T [Unpublished Data]

1.2 Methods of Measuring Surface Tension

The doubt regarding the surfactant's magneto-response comes from the way the surface tension is measured. Since surface tension is the energy per unit area at the interface, it can be difficult to measure it. A more advanced method used in the lab, uses a microbalance between the two surfaces to measure the surface tension. The tensiometer, which follows the Du Noüy ring method, places a small ring on the surface and measures the force required to pull the ring off the surface [6]. While this gives accurate results for the surface tension, it cannot easily incorporate a magnetic field into the system.

The previous magnetic surfactant studies used a method called the pendent drop method to measure surface tension [5]. This method calculates the surface tension from the dimensions of droplets suspended from the end of a needle. After taking a picture of the droplet to determine its dimensions, the following equation calculates the surface tension:

$$\gamma = \frac{\Delta\rho g D^2}{H} \quad (1)$$

where γ is the surface tension of the system (mN/m), $\Delta\rho$ is the density difference (g/cm³) between the inside and outside of the drop, g is acceleration due to gravity (m/s²), D is the maximum equatorial diameter of the drop (mm), and H is a shape factor calculated by

$$\frac{1}{H} = \frac{B_4}{S^a} + B_3 S^3 + B_2 S^2 + B_1 S - B_0 \quad (2)$$

where the values a , B_4 , B_3 , B_2 , B_1 , and B_0 are obtained from **Table 1** based on the value of S which is found from

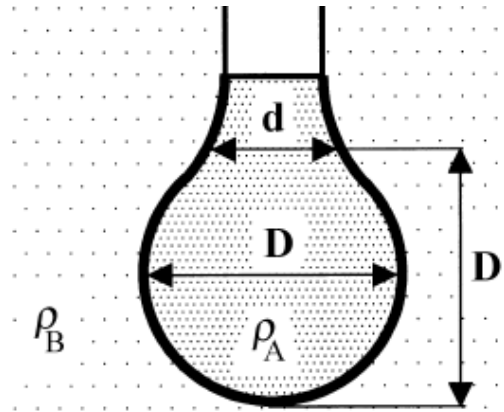
$$S = \frac{d}{D} \quad (3)$$

Table 1. Emperical Constants Used in Equation 2 [6]

Range of S	A	B ₄	B ₃	B ₂	B ₁	B ₀
0.401–0.46	2.56651	0.3272	0	0.97553	0.84059	0.18069
0.46–0.59	2.59725	0.31968	0	0.46898	0.50059	0.13261
0.59–0.68	2.62435	0.31522	0	0.11714	0.15756	0.05285
0.68–0.90	2.64267	0.31345	0	0.09155	0.14701	0.05877
0.90–1.00	2.84636	0.30715	-0.6912	-1.08315	-0.18341	0.20970

where D is the maximum equatorial diameter of the drop (mm) and d is the width of the drop (mm) measured at the distance D from the bottom of the drop as seen in **Figure 5** Error! Reference source not found..

Since the pendent drop method only relies on the ability to take a clear picture of the drop, it allows the easy incorporation of a magnetic field by forming the drop within the field; however, this method requires great attention to detail and cleanliness to obtain good results [6].

**Figure 5.** Illustration of the Variables Used in Calculating Surface Tension from the Pendent Drop Method

Additionally, as the pendent drop uses acceleration due to gravity to obtain the surface tension, it operates under the assumption that the suspended drop's net force only comes from the downward gravitational force and the upward force from the interfacial

tension. It does not consider any additional forces, such as magnetic forces, which could be acting on the system.

1.3 Magnetics and Their Effects

Since the possibility of magneto-responsive properties is the main reason for investigating the magnetic surfactants, it is important to understand the possible effects different types of magnetic fields can have on the surfactants. There are two different ways of obtaining magnetic fields: one is with a permanent magnet that produces its own persistent magnetic field and the other is a magnetic field that is produced by the movement of the charged particles in an electric current [7].

A permanent magnet is a magnetized ferromagnetic material that has both a north and south pole. Each magnet contains its own magnetic dipole moment, m , which points in a line from the magnet's northern pole to its southern pole. A collection of these small dipole moments models the magnetic field of larger magnets represented by the variable H that follows the magnetic pole model in which the opposite magnetic poles will either attract or repel each other. In this model, the magnetic dipole moment comes from

$$m = q_m d \quad (4)$$

Where m is the magnetic dipole moment in amps/m^2 , q_m is the magnetic pole strength in amps/m^3 and d is the distance vector (m). When a second magnet with its own dipole moment enters the first magnet's magnetic field, each magnetic pole will experience a different magnetic force based on the distance from the first magnet equal to

$$F = \nabla(m \cdot B) \quad (5)$$

Where F is the force in Newtons, m is the magnetic dipole moment in amperes per squared meters, and B is the magnetic flux density, or magnetic field, in Newtons per meter per ampere or Tesla [7]. The magnetic field quantity, H , relates to the B magnetic field using

$$B = \mu H \quad (6)$$

Where μ is the permeability of the magnetic field, H , through a medium with units of Newton per squared ampere [8].

When introducing the magnetic surfactants into the permanent magnet's magnetic field, the surfactant's magnetic poles will experience a force that pulls the surfactant toward the permanent magnet in the direction of increasing magnetic field strength. This extra magnetic force would act in addition to the downward gravitational force on the suspended surfactant. Since the pendant drop analysis only accounts for the gravitational force by using acceleration due to gravity in its calculations, the change in net force of the system could show up as a false change in the system's surface tension. Because of this possibility, we decided to investigate the surface tension within a parallel magnetic field.

An electrical current running through a conducting wire coil or "solenoid" yields a magnetic field defined as

$$H = \frac{NI}{L} \delta_z \quad (8)$$

where, N is the number of turns, I is the current in amps, L is the solenoid length, and δ_z is a unit vector in the direction of the solenoid's axis [8]. An infinitely long magnetic field would produce a uniform magnetic field inside the coil with no variation in

magnetic dipole moment and, therefore, no magnetic gradient to impose a force on the surfactants.

The purpose of this thesis is to investigate the previous data obtained using the pendent drop analysis over a permanent magnet that showed a reduction in the surface tension of magnetic surfactants. Because of the possibility of magnetic forces acting on the permanent magnet's system due to its magnetic strength gradient, we will use the same pendent drop methods within a parallel magnetic field to explore whether the surface tension drop came from a false effective force on the drop or from a change in energy at the interface.

2. EXPERIMENTAL

The experimental procedures include the synthesis of the cationic magnetic surfactants and the application of the pendent drop method without a magnetic field as well as within permanent and parallel magnetic fields.

2.1 Materials

The Hexadecyltrimethylammonium bromide ($C_{16}TAB$) used to form the magnetic surfactants came from *Sigma-Aldrich* (CAS 57-09-0) and was originally opened on September 27, 2012. The Cobalt (II) Chloride ($ClCo_2 \cdot 6H_2O$) was purchased from *Alfa Aesar* (CAS 7791-13-1), and the Iron (III) Chloride hexahydrate $Cl_3Fe \cdot 6H_2O$ came from *Acros Organics* (CAS 10025-77-1). Methanol from *Fisher Science Education* (CAS 67-56-1) was also used for the synthesis of the magnetic surfactants and to clean the glassware throughout the data taking process. A batch of Dysprosium based magnetic surfactant ($C_{19}H_{42}DyCl_3Br$) previously synthesized in house was also incorporated in the pendent drop analysis. Additionally, the surfactant solutions were formed at varying concentrations throughout the entire experimental process using ultra-pure, deionized water.

2.2 Equipment

A microscopic camera with USB plug-in capabilities took digital pictures of the droplets in all applications of the pendent drop analysis. A Hamilton brand gastight 1000 series syringe with a 19 gauge, blunt-ended needle was suspended from an arm attached to a ring stand giving enough room to form a droplet at the end of the needle. The pendent drop analysis over the permanent magnet was performed using the setup shown in **Figure 6**. Using a white paper backdrop with light from a lamp passing through it allows for a clearer depiction of the droplet and its edges. The setup does not vary from the setup for the pendent drop analysis with no magnetic field other than the use of a 0.6T magnet, which was bound in a wooden block for safety purposes. The setup for the pendent drop analysis in the parallel magnetic field, shown in **Figure 7**, is also very similar with a few

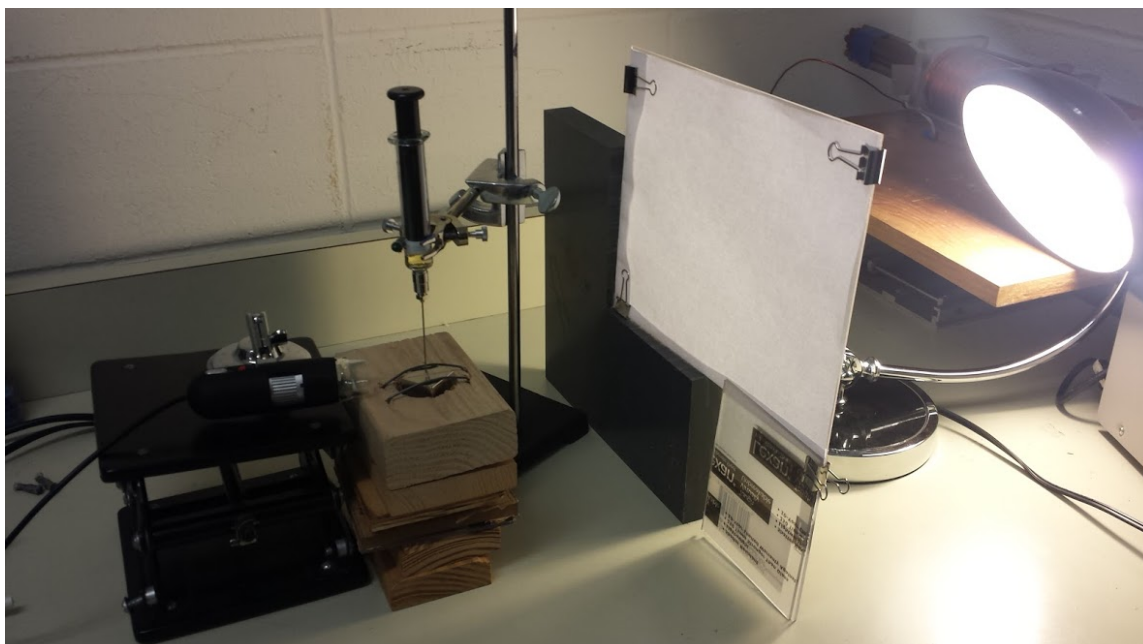


Figure 6. Setup Used for Taking Surface Tension Data over the Permanent Magnet

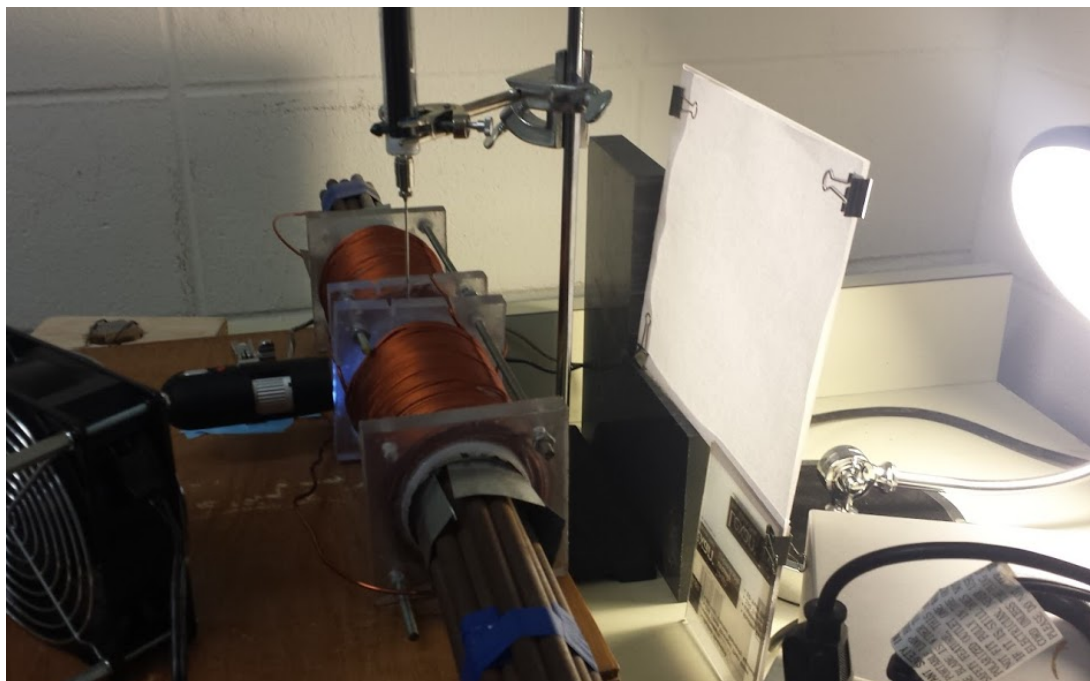
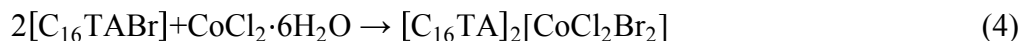


Figure 7. Setup Used for Taking Surface Tension Data inside a Parallel Magnetic Field changes. A 0-20 Amp electric current passing through the copper coil generates the magnetic field controlled by the current's power supply box. Additionally, the system contains a small computer fan placed just outside of the coil to help cool the system, and to minimize the magnetic interactions within the field, a blue Fischer brand capillary tube was used in place of a blunt end needle by attaching it to the needle end with vacuum grease. Finally, an image analysis software from Olympus allowed for the accurate and repeatable analysis of the drop images taken in all systems.

2.3 Procedures

2.3.1 Synthesis of Cobalt Based Magnetic Surfactants

A cobalt based magnetic surfactant was synthesized using 8.49 g of the $C_{16}TAB$ and 2.27 g of the Cobalt (II) Chloride to obtain the ideal 2:1 molar ratio needed for the following chemical reaction:



Steps I – VII of the synthesis, “Production of Magnetic Surfactant,” procedure from Paul Scovazzo (updated June 3, 2015 version) was used with the following variations:

- Approximate volumes of methanol were used in steps II and III (1 gram to 3.5-4.1 mL methanol ratio in step II and 1 gram to 4.4 mL methanol ratio in step III)
- Heated and stirred the C_{16}TABr in methanol solution to fully dissolve (step II)
- Refrigerated the solution to obtain three phases/layers of liquids/solids as supposed to the solid-solid solution obtained from freezing (step VII)

After these steps, the solution was filtered to obtain purified crystals that were then dissolved in 10 mL of methanol at 30°C to repeat the filtering purification process. This purification process was repeated two times more using first 15 mL of methanol and then 10 mL of methanol. Instead of filtering the crystals from the last 10 mL of methanol, a rotovac distillation was used for about an hour. The remaining product yielded 0.40 g of the $[\text{C}_{16}\text{TA}]_2[\text{CoCl}_2\text{Br}_2]$ giving a final product percent recovery of 4.0%.

2.3.2 Synthesis of Iron Based Magnetic Surfactant

The iron based magnetic surfactants were synthesized using 6.92 g of the C_{16}TABr and 5.13 g of the Cobalt (II) Chloride to obtain the ideal 1:1 molar ratio needed for the following chemical reaction:



Steps I – IX of the synthesis, “Production of Magnetic Surfactant,” procedure from Paul Scovazzo (updated June 3, 2015 version) was used with the following variations:

- Approximate volumes of methanol were used in steps II and III (1 gram to 4.3 mL methanol ratio in step II and 1 gram to 4.1 mL methanol ratio in step III)

- Heated and stirred the $C_{16}TABr$ in methanol solution to fully dissolve (step II)
- Heated the solution to completely dissolve the $FeCl_3 \cdot 6H_2O$
- Left container in freezer overnight, allowed to thaw in refrigerator for 10-15 minutes, then froze for only 5 minutes (step VII)
- Poured off excess fluid and added only enough methanol (at $50^\circ C$) to dissolve the crystals again (step VII)
- Repeated steps VII and VIII twice more filtering to remove the liquid both times instead of pouring it off (step IX)

After these steps, the filtered crystals were placed in a covered ceramic bowl and left to dry over the weekend. After drying, the remaining product yielded 3.22 g of the $[C_{16}TA][FeCl_3Br]$ giving a final product percent recovery of 32.2%.

2.3.3 Pendent Drop Analysis with No Magnetic Field

0.119 grams of the $C_{19}H_{42}DyCl_3Br$ magnetic surfactant was added to 150 mL of the ultra-pure water. The solution was then heated to about $70^\circ C$ and stirred to ensure all of the surfactant dissolved in the water. The resulting 150 mL of the 1.25 mM solution was then used to create the solutions with other concentrations by measuring the needed amount of the base solution to obtain the appropriate moles of magnetic surfactant for 25 mL of the desired concentration as shown in **Table 2**. The base solution volumes were measured with an Eppendorf micro-pipet and added to a 25 mL volumetric flask which was then filled the rest of the way with the ultra-pure water to create the solution. The syringes were prepared by pulling in about 5 mL of the solution and then wasting it three separate times to ensure the syringe was purged of any contaminants that would alter the solution during measurement. After the purging process, the needle was once again filled

Table 2. Volume Required to Create 25 mL of Varied Concentrations of Magnetic Surfactant Solution with a Dysprosium Counter Anion							
Concentration Forming (mM)	0.18	0.36	0.53	0.71	0.89	1.07	1.25
Moles Needed per 25 mL of solution (μmol)	4.50	9.00	13.25	17.75	22.25	26.75	31.25
Volume of Base Concentration Required (mL)	3.6	7.2	10.6	14.2	17.8	21.4	25.0

with the solution and then held upside down to remove as many air bubbles as possible before placing it on the ring stand to begin taking measurements. Once on the ring stand, the syringe was pushed to form small droplets of the solution. After the drops stabilized, signified by their lack of motion on the computer screen image, the camera took a digital picture of the drop, and the syringe pulled the existing drop back into the syringe to repeat the process for two new droplet pictures. If the liquid was seen to rise up the edges of the needle, the needle was removed from the system, wiped with methanol on a paper towel and then placed back into the system to continue taking data. After all the data was taken for one of the concentrations, the needle was removed, emptied, cleaned with methanol, and allowed to air dry before repeating the process with another concentration.

2.3.4 Pendent Drop Analysis over a Permanent Magnet

The analysis over the permanent magnet followed the same procedure as the procedure with no magnetic field with very few differences. The solutions were formed in the same way for the both the Dysprosium and Iron counter anion magnetic surfactants with the base solution containing 0.095 grams of the Iron (III) Chloride hexahydrate in 150 mL of the ultra-pure water and the volume amounts needed to create the specified

Table 3. Volume Required to Create 25 mL of Varied Concentrations of Magnetic Surfactant Solution with an Iron Counter Anion

Concentration Forming (mM)	0.15	0.31	0.44	0.57	0.78	1.00	1.20
Moles Needed per 25 mL of solution (μmol)	3.75	7.75	11.00	14.25	19.50	25.00	30.00
Volume of Base Concentration Required (mL)	3.13	6.46	9.17	11.88	16.25	20.83	25.00

concentrations shown in **Table 3**. After following the same needle preparation procedure, the needle was placed on the ring stand at a specific height each time marked by painted nail polish on the ring stand where the arm needed to be attached and on the syringe where it needed to be held by the ring stand. Additionally, the magnet was marked with an “X” to ensure the needle was centered over the magnet each time so that the solution was exposed to the same average magnetic field strength each time. The same cleaning process was used as well.

2.3.5 Pendent Drop Analysis inside a Parallel Magnetic Field

The analysis in the parallel magnetic field followed the same process for preparing the solutions, preparing the syringe, and cleaning the syringe as the previous methods; however, the main differences occurred while taking the data. Since the electric current heated the environment surrounding the droplet, the droplet began evaporating while waiting for it to reach steady state indicated by its slow, steady decrease in size over time. To prevent this evaporation, the pictures of the drop were taken as soon as possible after forming the drop. Then, to maintain the proper concentration at the needle end, the original drop was allowed to fall off the needle so that a new drop could be formed in its place. After one concentration was completely finished, the syringe was

removed and the inside of the magnetic field dried of any left behind solution. The capillary tube was cleaned by allowing methanol used for cleaning the syringe and its needle to flow from the needle through the capillary tube. This process was repeated to obtain three data points for each concentration at each magnetic field strength.

3. RESULTS

3.1 Surface Tension Measured over a Permanent Magnet

Applying the pendent drop method to the dysprosium based magnetic surfactant with and without a permanent magnet gave the results displayed in **Figure 8**. The results in red show the surface tension taken without a magnetic whereas the blue represents the data taken over a permanent magnet. The data suggests only a slight decrease in surface tension caused by the magnetic field as compared to the unpublished results taken with the cobalt based magnetic surfactant; however, the needle was further away from the magnet so that the drop experienced a significant decrease in magnetic field strength

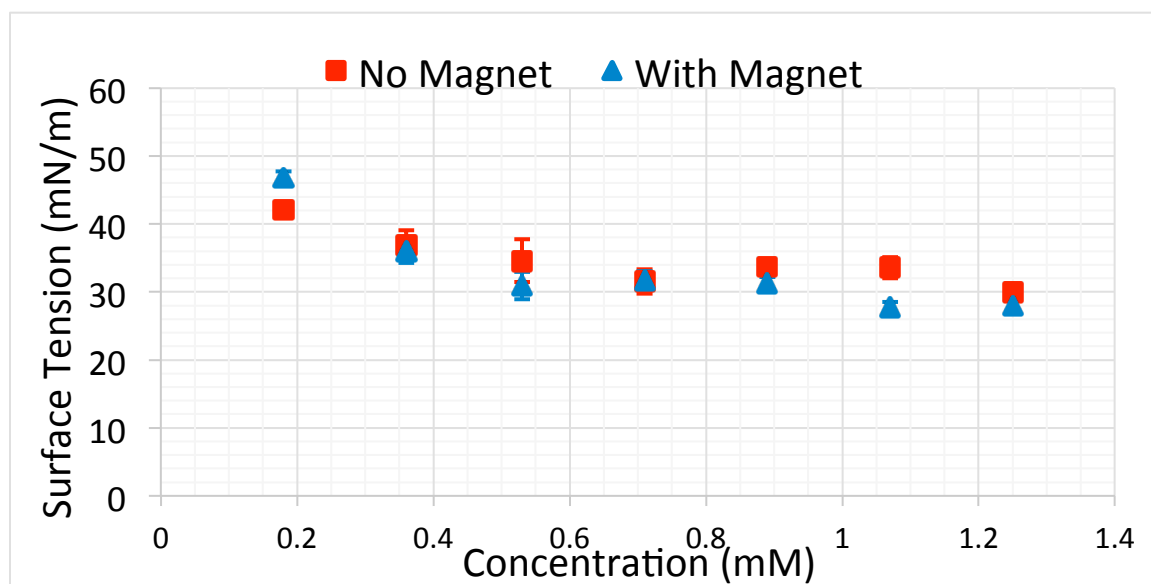


Figure 8. Effect of a Permanent Magnet on the Surface Tension of the Magnetic Surfactant $[C_{16}TA][DyCl_3Br]$ Under a Magnetic Field Strength of 0.6-0.27 T

while being measured. While some of the data between the measurements over a magnet and without a magnet overlapped, the general trend agreed with the surface tension decrease seen in the previous results.

Performing the same methods for the iron magnetic surfactant gave similar results as well as seen in **Figure 9**. The blue data points taken over the permanent magnet overall show a decrease in surface tension from the red points taken outside of any magnetic field. Again, while some of the data overlaps, the general trend matches the results seen with the Dysprosium and Cobalt counter anion magnetic surfactants.

Of importance is the fact that both the iron and the dysprosium magnetic surfactants showed a much less drastic change in the measured surface tensions from no magnetic field to the permanent magnet. When forming the drops, a clear picture for accurate analysis requires as large of a drop as possible. While moving the camera closer to the droplets adds to their size in the picture, the droplets also must be the largest size

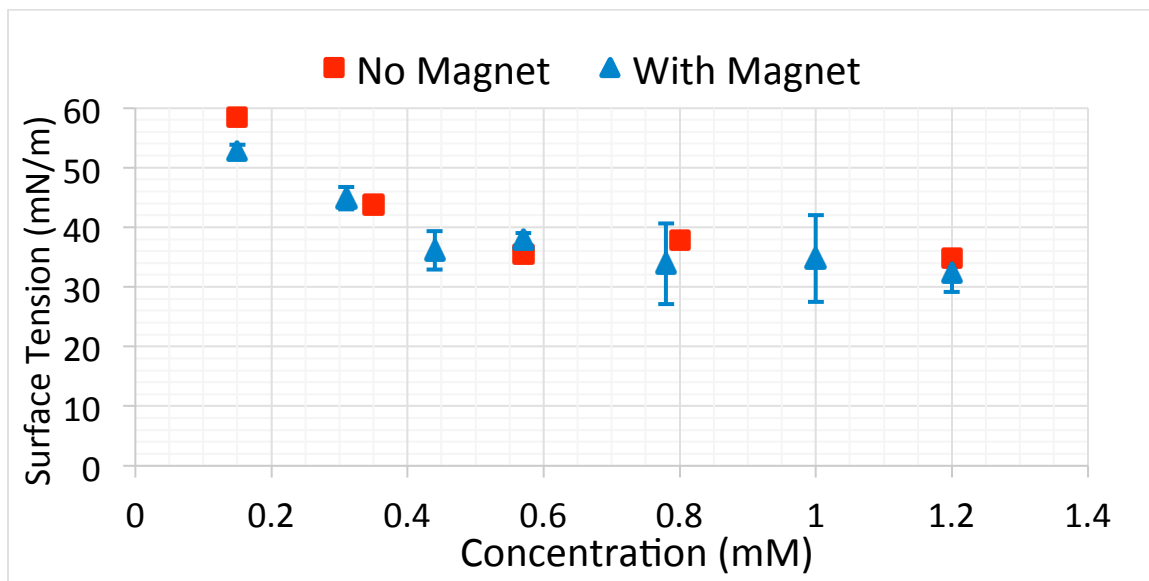


Figure 9. Effect of a Permanent Magnet on the Surface Tension of the Magnetic Surfactant $[C_{16}TA][FeCl_3Br]$ Under a Magnetic Field Strength of 0.6-0.13 T

possible before they fall off of the needle. This reduces the gradient in coloration at the edges as shown in **Figure 10**. When creating the larger sized drops, the drops fell off the needle when they were too close to the magnet, so the distance between them was increased to prevent this falling off; however, the small increase in distance caused a significant decrease in the magnetic field seen by the drop. The decreased magnetic field strength most likely caused the surface tension change in the drop to decrease as well.

3.2 Surface Tension Measured in the Parallel Magnetic Field

We evaluated the surface tension of the iron magnetic surfactant in the parallel magnetic field using electrical currents at 0, 5, 10, 15, and 19.5 Amps, which provided the analysis at different field strengths giving the results as shown in **Figure 11**. The measurements taken at the lower field strengths did not yield in a significant change in

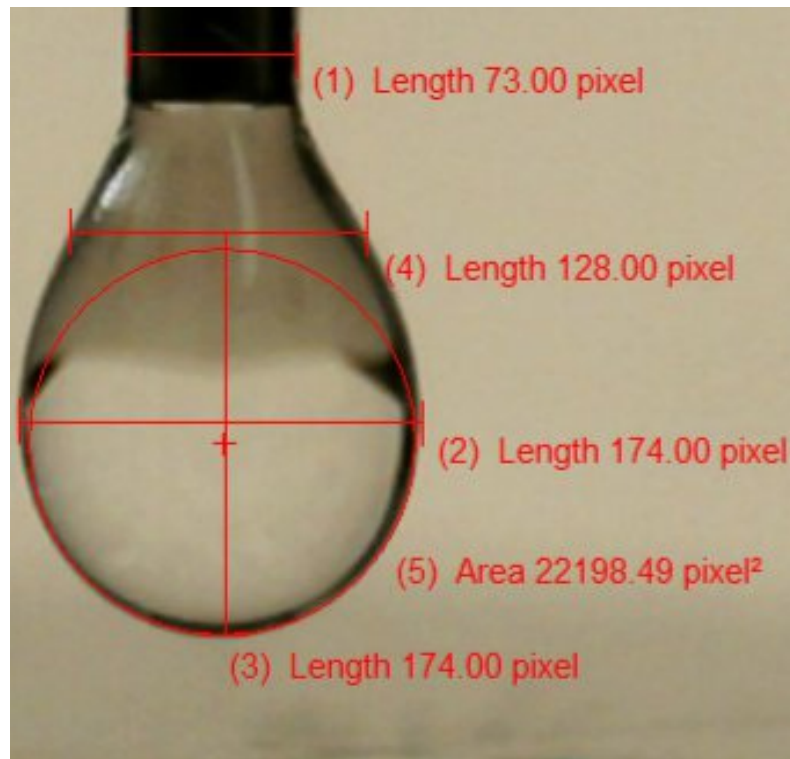


Figure 10. Example Photo of the Shape Analysis Performed on the Droplets

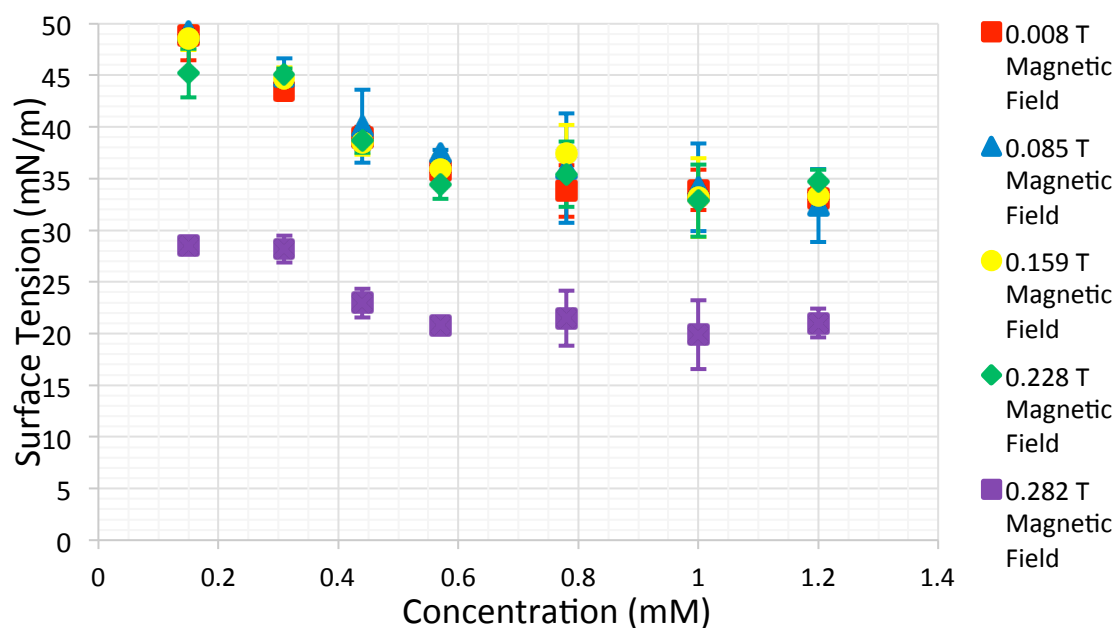


Figure 11. Surface Tension Measurements of the Magnetic Surfactant [C16TA][FeCl3Br] Performed in a Parallel Magnetic Field at Varied Field Strengths

surface tension with the measured values significantly overlapping; however, the stronger magnetic field strength resulted in a visible drop in surface tension as shown with the purple data points.

4. DISCUSSION AND CONCLUSION

One of the problems with the pendent drop method is that it relies on the assumption that the only forces on the suspended drop comes from the downward gravitational force and the surface forces. Applying a permanent magnet to the system could have added an extra magnetic force not accounted for in the surface tension calculations; however, since the parallel magnetic field produces a uniform field within the coil, it would not cause a force on anything within the field. Therefore, the reduction in surface tension measured in the parallel magnetic field supports the idea that the surface tension changes due to a change in surface energy rather than an artificial gravity on the drop. It is important to note that the effect of the magnetic field were only quantifiable at the higher magnetic field strengths (≥ 0.28 Tesla).

To find the root cause of this phenomenon, the magnetic response of the other magnetic surfactants will be investigated inside the parallel magnetic field. The future findings will help in the exploration of the possibilities involved with this new field of study.

REFERENCES

- [1] M. J. Rosen and J. T. Kunjappu, *Surfactants and Interfacial Phenomena*, Hoboken, New Jersey: John Wiley & Sons, Inc., 2012.
- [2] G. T. Barnes and I. R. Gentle, *Interfacial Science: and Introduction*, New York: Oxford University Press Inc., 2011.
- [3] C. O. Rangel-Yagui, A. Pessoa-Jr and D. Blankschtein, "Two-phase aqueous micellar systems: an alternative method for protein purification," *Braz. J. Chem. Eng.*, vol. 21, no. 4, pp. 531-544, 2004.
- [4] P. Brown, A. Bushmelev, C. P. Butts, J.-C. Eloi, I. Grillo, P. J. Baker, A. M. Schmidt and J. Eastoe, "Properties of New Magnetic Surfactants," *Langmuir*, vol. 29, no. 10, pp. 3246-3251, 2013.
- [5] P. Brown, A. Bushmelev, C. P. Butts, J. Cheng, J. Eastoe, I. Grillo, H. R. K. Schmidt and A. M., "Magnetic Control over Liquid Surface Properties with Responsive Surfactants," *Angewandte Chemie International Edition*, vol. 51, no. 10, pp. 2414-2416, 2012.
- [6] J. Drelich, C. Fang and C. L. White, "Measurement of interfacial tension in Fluid-Fluid Systems," in *Encyclopedia of Surface and Colloid Science*, Marcel Dekker Inc., 2002, pp. 3152-3166.
- [7] "Magnetic field," Wikipedia, the Free Encyclopedia, 20 April 2016. [Online]. Available: with the solution and then held upside down to remove as many air bubbles as possible before . [Accessed 10 May 2016].
- [8] P. Scovazzo, C. A. Portugal, A. A. Posatella, C. A. Afonso and J. G. Crespo, "Hydraulic pressures generated in Magnetic Ionic Liquids by paramagnetic fluid/air interfaces inside of uniform tangential magnetic fields," *Journal of Colloid and Interface Science*, vol. 428, pp. 16-23, 2014.